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Journal Item

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Energy Procedia 61 (2014) 2327 – 2330

Energy Procedia

The 6th International Conference on Applied Energy – ICAE2014

Experimental and Numerical Investigation of The Effect of Pellet Size on the adsorption Characteristics of Activated Carbon/Ethanol

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Abstract

Low temperature adsorption cooling is an attractive heat powered cooling technology suitable for various applications where waste heat is available. The use of activated carbon as adsorbent with ethanol offers potential for low temperature cooling applications like the food retail industry. Activated carbons are commercially available in the form of powders, granules and pellets. Although powder materials have the advantage of good adsorption kinetics but they are difficult to integrate in adsorption beds. Pellets and granules come at various shapes and sizes and can be effectively accommodated in adsorption beds but offer slower kinetics compared to the powder form. This work experimentally and numerically investigates the effect of pellet size on the ethanol adsorption characteristics of Norit RX3 activated carbon. Dynamic vapour sorption (DVS) testing was used for measuring the adsorption isotherms and kinetics for a range of pellet lengths ranging from 3mm to 12mm. COMSOL Multiphysics was used to simulate the adsorption effect taking into account the diffusion process. Results showed that increasing the pellet dimension in terms of diameter and length reduces the adsorption kinetics.

Peer-review under responsibility of the Organizing Committee of ICAE2014
Keywords: Activated carbon, ethanol, adsorbent, COMSOL, adsorption kinetics;

1. Introduction

Several investigations have been carried out to study the performance of pellet adsorbents. Henninger et al. [1] tested several activated carbons in pellet form with methanol at -5 °C and 7 °C evaporation temperatures. Activated carbons with narrow pores showed high specific energy which is advantageous

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Peer-review under responsibility of the Organizing Committee of ICAE2014
doi:10.1016/j.egypro.2014.11.1195

Nomenclature

C	Gas concentration (mol/m^3)	Cp	specific heat (J/kg.K)
D_{eff}	Effective diffusivity (m^2/s)	ΔH	Heat of adsorption (kJ/kg)
p/p_s	Partial pressure ratio (-)	ε	Bed porosity (-)
T	Temperature (°C)	t	Time (sec)
λ_{eff}	Bed thermal conductivity (W/m. K)	x	Equilibrium ethanol uptake (kg/kg_{ads})

for low evaporation (<0 °C), higher desorption (>110 °C) and higher heat rejection (>30 °C) temperatures. Yurtsever [2] tested ethanol, acetone, and n-pentane with activated carbon pellets with 2 mm diameter and 2-4 mm length using a gravimetric analyzer for heat pump application. The ratio between the inner and outer radii of the bed was 0.5; Simulations were done on three different beds having outside diameters of 2.5 cm, 5 cm and 10 cm. Although the three fluids are non-toxic, ethanol showed better performance than other fluids. Decreasing the annular bed radius was found to make the internal temperature profile more homogeneous which improves the adsorbent kinetics. Aittomäki and Härkönen [3] tested methanol /zeolite pellets heat pump at evaporation temperatures ranging from -5 °C to 5 °C and condensation temperatures ranging from 35 °C to 45 °C and desorption temperature up to 230 °C. They concluded that to obtain a short cycle time, a high conductivity is necessary, otherwise, a small bed thickness < 20 mm must be used. Restuccia et al. [4] tested zeolite-Y/methanol pair in pellet and coating forms; fixed bed adsorber with zeolite pellets showed less specific cooling power and longer cycle time. Limited studies reported the effect of pellet dimensions on the adsorption performance; therefore this study investigates the effect of RX3 activated carbon pellet size on its adsorption kinetics. Fig 1a shows an SEM image of the 3 mm pellet with average diameter of 2.57 mm.

2. Adsorption isotherms and kinetics

In this investigation a dynamic vapour sorption (DVS) gravimetric analyser has been used to study the ethanol adsorption characteristics (adsorption isotherms, kinetics) of activated carbon RX3 with different pellet lengths of 3, 6, 9 and 12mm. The adsorption isotherms data were fitted with the Langmuir model as shown in fig 1b. Fig 1c presents the fractional uptake at 25 °C versus the adsorption time at p/ps=10%; it is observed that increasing the pellet length increases the time required to achieve the equilibrium uptake.

3. CFD modelling of adsorption process

COMSOL Multiphysics software was used to solve the continuity, momentum and energy equations to simulate the adsorption of ethanol on the pellets of activated carbon taking into account the diffusion process described by [5, 6]. The mass balance and pressure distribution inside the pellet were expressed by equations 1 and 2, respectively.

$$\frac{\partial C}{\partial t} - \nabla \cdot \left(D_{eff} \nabla C\right) = -\frac{\rho_b}{M * \varepsilon} \frac{\partial x}{\partial t} \quad (1) \qquad p = C * R_{universal} * T \quad (2)$$

The energy balance and the change of adsorption uptake are expressed by equations 3 and 4:

$$(\rho Cp)_{eff} \frac{\partial T}{\partial t} = \nabla \cdot \left(\lambda_{eff} \nabla T\right) + \rho_b \Delta H \frac{\partial x}{\partial t} - \rho_b Cp_v x \frac{\partial T}{\partial t} \quad (3) \qquad \text{where} \quad \frac{\partial x}{\partial t} = \left(\frac{\partial x}{\partial T}\right)_{p=const} \frac{\partial T}{\partial t} + \left(\frac{\partial x}{\partial p}\right)_{T=const} \frac{\partial p}{\partial t} \quad (4)$$

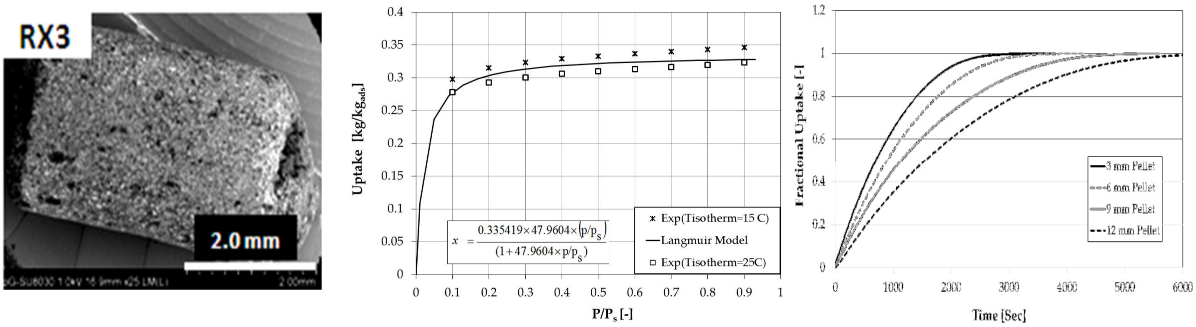


Fig. 1. (a) SEM of 3 mm of RX3 (b) Langmuir isotherm model (c) Fractional uptake of different pellets

$(\partial x/\partial T)_{p=const}$ and $(\partial x/\partial p)_{T=const}$ were calculated by differentiating Langmuir isotherm and $\partial p/\partial t$ was calculated by differentiating equation 2. In this simulation, the pellet diameter, bulk density, porosity and effective diffusivity of 2.57mm, 380kg/m^3, 0.75 and $1.3*10^{-6}$m^2/s were used. The boundary conditions in fig 2a were set to isotherm temperature at the bottom of the pellet and constant concentration at boundaries 3 and 4 (very fine mapped mesh was used). The convective cooling heat transfer coefficient was set to 50 W/m.K based on recommended values by Füldner and Schnabel [5]. Fig 2b compares the DVS measurements and the CFD isotherm prediction for the 9 mm pellet with a mean relative deviation of ± 10 % while fig 3 presents the predicted uptake, pressure and temperature of the pellet at 400 s adsorption time. Regarding the effect of pellet diameter, fig 4a presents the effect of pellet diameter (1.5, 2.0, 2.5 and 3.0mm) on the adsorption kinetics for pellet length of 6mm. It is clear from this figure that as the pellet diameter decreases, the time required to reach equilibrium decreases. Fig 4b presents the effect of adsorption temperature on the adsorption kinetics for pellet length of 6 mm and diameter of 2.57 mm. It is clear from this figure that higher adsorption temperatures reduce the equilibrium uptake.

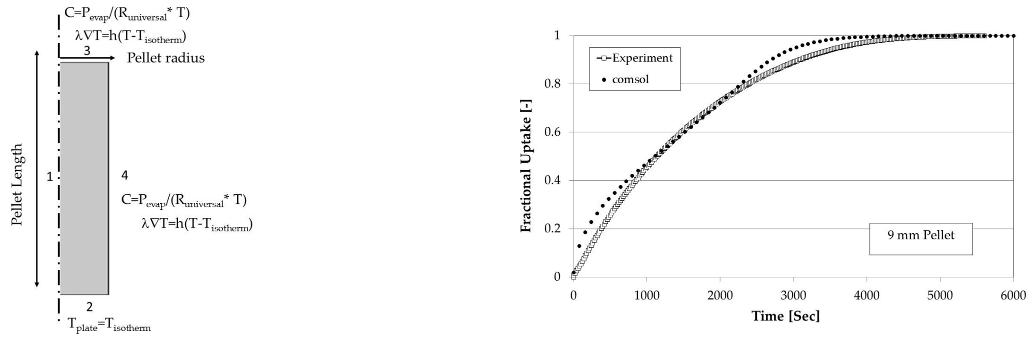


Fig .2. (a) Model boundary conditions (b) Model validation

4. Conclusions

Activated carbon / ethanol adsorbent pair offers potential in low temperature cooling applications such as food preservation and ice making. The pellet size has an effect on the bed design and the adsorption characteristics. This work investigated experimentally and numerically the effect of pellet diameter and pellet length on ethanol adsorption characteristics. Results showed that increasing the pellet size (diameter or length) causes slower adsorption kinetics. Also, increasing the adsorption temperature leads to reduction in adsorption capacity.

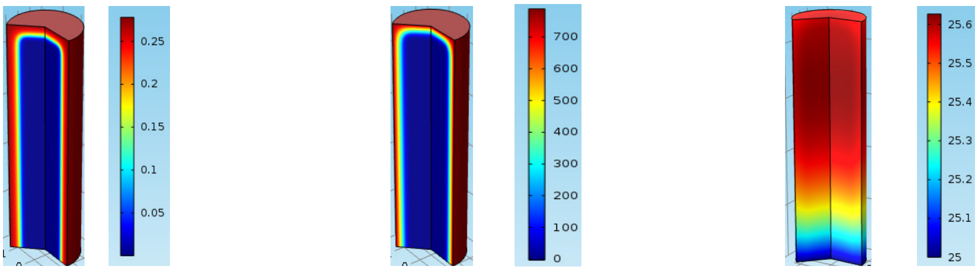
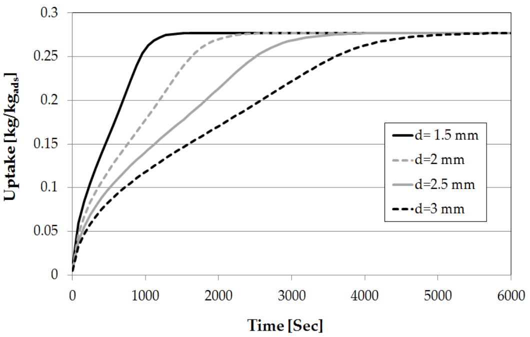


Fig.3. (a) Uptake [-] (b) Pressure [Pa] (c) Temperature[°C]



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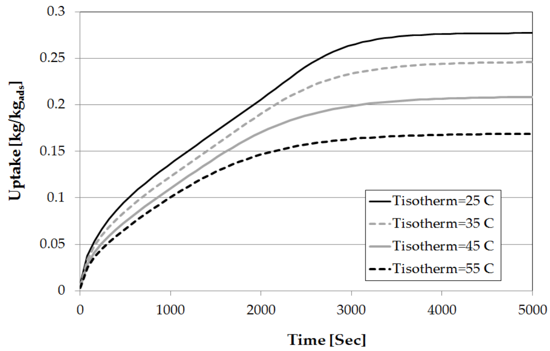

Fig. 4. (a) Effect of pellet diameter (b) Effect of adsorption temperature

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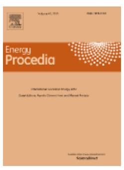

Biography

Ahmed Elsayed is a research associate at University of Birmingham with a PhD in thermal engineering. He has experience in modelling and testing of boiling and condensation heat transfer, currently he is working on adsorption refrigeration project.